

Mechanism of Soil Water and Nitrogen Transport and Redistribution under Aerated Subsurface Drip Irrigation

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ABSTRACT: To reveal the intrinsic mechanisms of soil water and nitrogen transport and redistribution under aerated subsurface drip irrigation, this study conducted indoor soil box experiments with two irrigation methods: aerated irrigation (A) and conventional irrigation (C). Combining three drip irrigation tape burial depths ($H=0, 10, 20$ cm) and two emitter flow rates ($q=2, 5.5$ L/h), the redistribution patterns of soil moisture, ammonium nitrogen, nitrate nitrogen, and pH at 0, 2, and 5 days after irrigation were systematically analyzed, with soil aeration indicators and microbial mechanisms introduced for explanation. The main conclusions are as follows: (1) Aeration irrigation significantly alters the preferential movement of water, promoting the vertical migration of the wetting front, whereas under conventional irrigation, the wetting front tends to expand horizontally. When the buried depth of the drip irrigation tape increases to 20 cm, the promoting effect of aeration irrigation on vertical water movement is most significant. The greater the Drip head flow rate, the stronger the promoting effect of aeration irrigation on horizontal water movement. (2) Aeration irrigation significantly increased soil dissolved oxygen concentration and oxidation-reduction potential, optimized soil aeration environment, and consequently promoted the conversion of ammonium nitrogen to nitrate nitrogen. Compared to conventional irrigation, oxygenated irrigation increases soil nitrate nitrogen content by 5.35%-6.27% in the deeper vertical layer (30-40 cm), while ammonium nitrogen content decreases by 3.65%-4.12%, and the trend of soil acidification (reduction in pH) becomes more pronounced. (3) From a microbial mechanism perspective, oxygenated irrigation upregulated the abundance of genes related to nitrification (e.g., *amoA/C*) and the genus *Nitrosospira*, while simultaneously suppressing the expression of denitrification genes (e.g., *narG*), explaining the accumulation of nitrate nitrogen and the reduction of ammonium nitrogen at the functional gene level. This study provides a theoretical basis for optimizing the parameters of aerated subsurface drip irrigation and regulating the soil water and nitrogen environment.

KEYWORDS: Aerated subsurface drip irrigation; Water and nitrogen transport; Redistribution; Drip tape burial depth; Emitter discharge rate; Nitrogen cycling microorganisms

I. INTRODUCTION

Water scarcity and low fertilizer utilization efficiency are critical bottlenecks constraining sustainable agricultural development. Drip irrigation, particularly subsurface drip irrigation, has become a core water-saving technology due to its significant reduction in ineffective evaporation and deep percolation [1, 2]. However, traditional subsurface drip irrigation, characterized by concentrated water application and underground placement, often leads to a "saturated-anoxic" condition in the crop root zone, inducing hypoxia stress and inhibiting crop root respiration and nutrient uptake [3, 4].

Aerated Subsurface Drip Irrigation (ASDI), which delivers micro-nano bubble water or oxygenated water to the root zone to improve soil aeration, has emerged as a cutting-edge technology to address the aforementioned challenges [5, 6]. Existing studies have demonstrated that aerated irrigation significantly increases soil dissolved oxygen concentration and redox potential, enhances aerobic microbial activity, and consequently influences the transformation processes of soil nitrogen [7, 8]. However, most current research has focused on the effects of aeration on crop growth and yield [9], while the synergistic impact of key irrigation technical parameters (such as drip tape burial depth and

emitter discharge rate) on the transport and redistribution processes of water and nitrogen in the soil under aerated conditions. Particularly, the underlying physical-biological-chemical coupling mechanisms remains insufficiently explored.

Therefore, this study introduces an aeration variable based on traditional research on water and nitrogen redistribution. Through indoor soil box simulation experiments, it systematically investigates the effects of aeration irrigation on the redistribution patterns of soil moisture, ammonium nitrogen, and nitrate nitrogen under different buried depths of drip irrigation belts and emitter flow rates. Combined with soil aeration indicators and functional gene analysis of nitrogen-cycling microorganisms, the study elucidates the underlying mechanisms, aiming to provide theoretical support for the scientific design and precise management of aerated subsurface drip irrigation systems.

II. MATERIALS AND METHODS

2.1 Experimental Design

The experiment was conducted at the Hydraulic Laboratory of the National Civil Engineering Experimental Teaching Demonstration Center of Hunan City University. The test soil was a silty loam (sand 14.9%, silt 23.1%, clay 62.0%) with a bulk density of 1.2 g/cm³. The experimental setup included a 30° sector-shaped glass soil tank, a peristaltic pump, an irrigation water source (ammonium sulfate solution, 500 mg/L), and an aeration device (micro-nano bubble generator).

The experiment employed a three-factor partial factorial design:

- (1) Irrigation Method (I): Conventional Subsurface Drip Irrigation (C), Aerated Subsurface Drip Irrigation (A, dissolved oxygen concentration ~15 mg/L).
- (2) Dripline Burial Depth (H): 0 cm (surface), 10 cm, 20 cm.
- (3) Emitter Flow Rate (q): 2 L/h, 5.5 L/h.

The irrigation volume was controlled at 7.2 L. A total of $2 \times 3 \times 2 = 12$ treatments were applied. After irrigation, soil samples were collected at 0, 2, and 5 days to measure moisture content, ammonium nitrogen, nitrate nitrogen, and pH, while simultaneously monitoring soil dissolved oxygen concentration (DO) and redox potential (Eh). The experimental treatments and sampling methods were based on previous studies [10, 11].

2.2 Measurement Indicators and Methods

- Soil moisture: Oven-drying method.
- Ammonium nitrogen, nitrate nitrogen: Leici water quality analyzer (DGB480).
- Soil pH: Determined by pH meter.
- Soil dissolved oxygen (DO) and oxidation-reduction potential (Eh): Portable dissolved oxygen/oxidation-reduction potential meter.

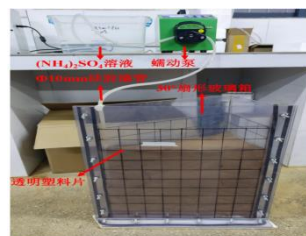


Figure 2-1 Physical diagram of drip irrigation system device

2.3 Microbial Mechanism Analysis (Supplementary)

To elucidate the effects of oxygenation on nitrogen transformation, soil samples from key treatments (H=10 cm, q=2 L/h) were selected and analyzed using metagenome sequencing technology to examine nitrogen cycling functional genes (amoA, narG, nosZ, etc.) and microbial community structure changes in *Broussonetia papyrifera* [8].

III. RESULTS AND ANALYSIS

3.1 Effects of Aeration Irrigation on Water Redistribution

3.1.1 Influence of Drip Irrigation Tape Burial Depth

Figure 3-1,3-2 illustrates the soil moisture contour lines under conventional and oxygenated irrigation with different buried depths of drip irrigation tapes. Compared with conventional irrigation, oxygenated irrigation significantly alters the shape of the wetting front. At H=0 cm, the wetting front under conventional irrigation appears as a "prostrate" semi-ellipse, whereas under oxygenated irrigation, the vertical migration distance is markedly increased. At H=10 cm and 20 cm, the wetting front under oxygenated irrigation treatment exhibits a more pronounced "upright" semi-elliptical shape, with the vertical migration distance increasing by an average of 15%-20% compared to conventional irrigation. This indicates that oxygenated irrigation, by improving soil aeration, reduces the surface tension of water and enhances the vertical infiltration capacity driven by gravitational potential [6].

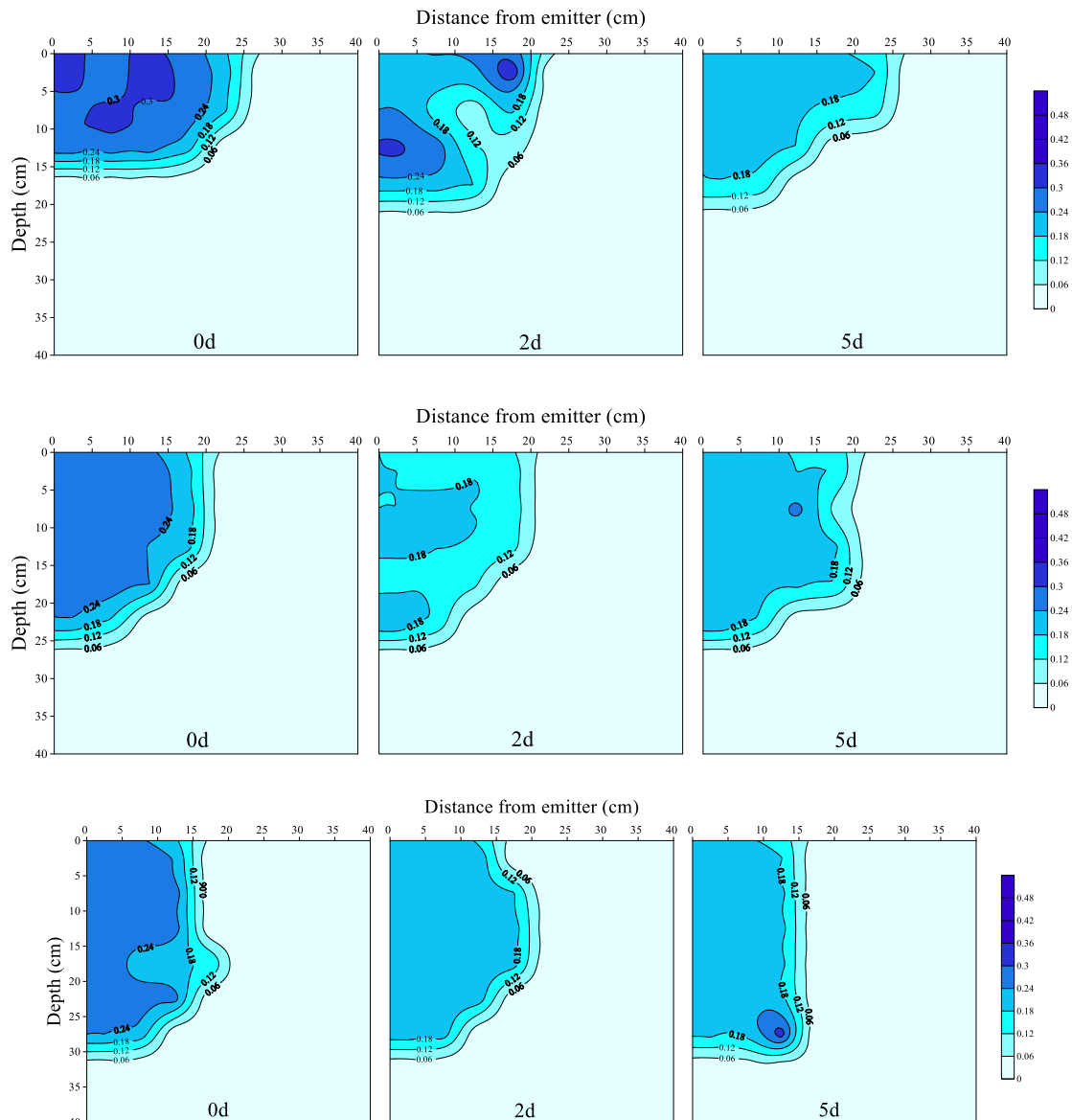


Figure 3-1 Isohyric curve of soil moisture content for drip head flow rate $q=2L/h$

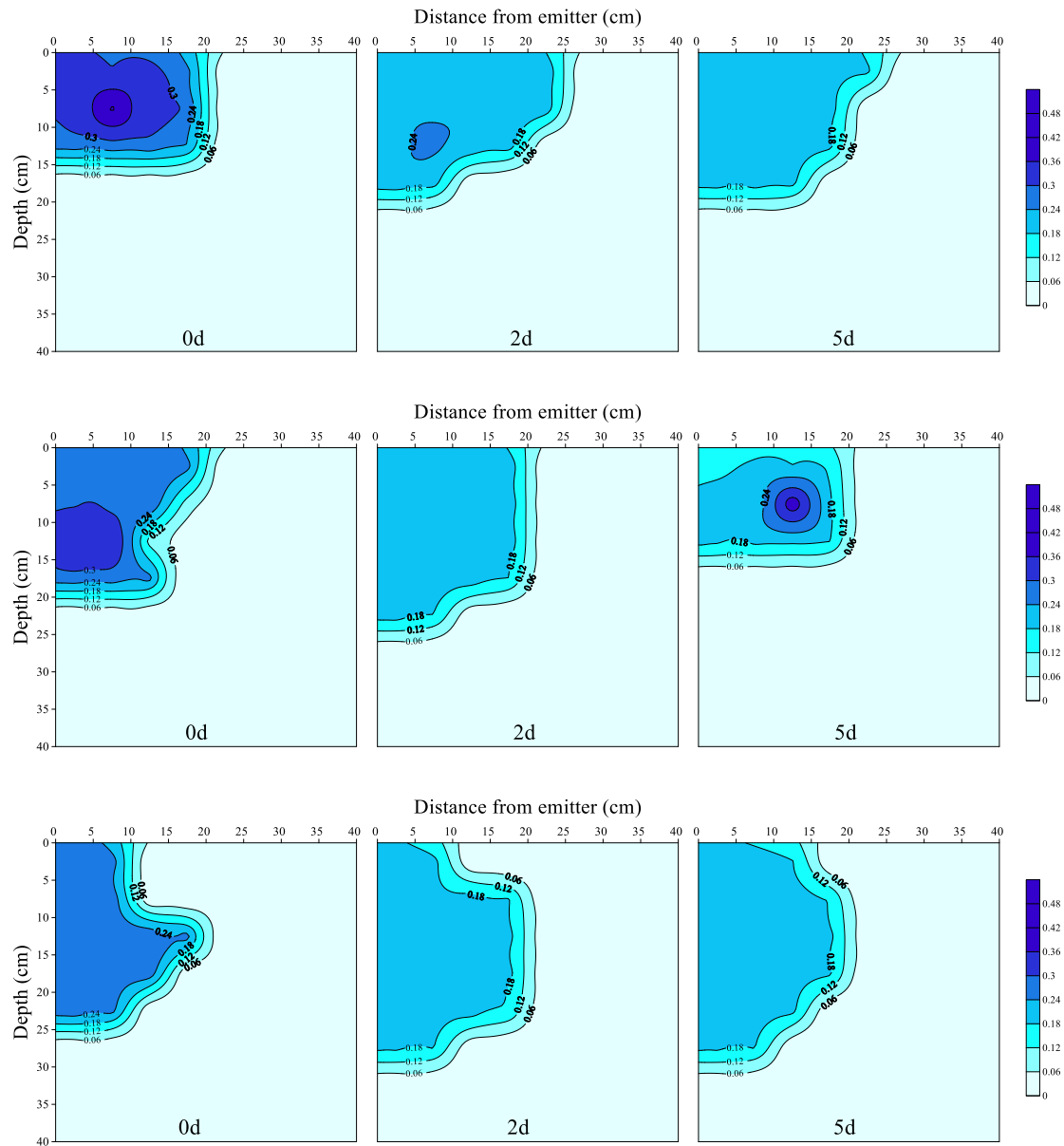


Figure 3-2 Isohyric curve of soil moisture content for drip head flow rate $q=5.5L/h$

3.1.2 Influence of Emitter Flow Rate

The emitter discharge rate exhibits an interaction effect with irrigation methods on moisture redistribution. On the day of irrigation completion (0d), the wetting front area under the small discharge rate (2 L/h) treatment was larger than that under the high discharge rate (5.5 L/h). However, after 2d and 5d of redistribution, the wetting front area under the high discharge rate treatment surpassed that of the small discharge rate treatment, particularly under aerated irrigation conditions, where the larger emitter discharge rate demonstrated a more pronounced effect on the horizontal redistribution of moisture (Figure 3-3,3-4 and3-5). This may be attributed to the faster initial infiltration under the high discharge rate, resulting in a wider wetted body, followed by more active horizontal redistribution driven by the matric potential gradient enhanced by aeration.

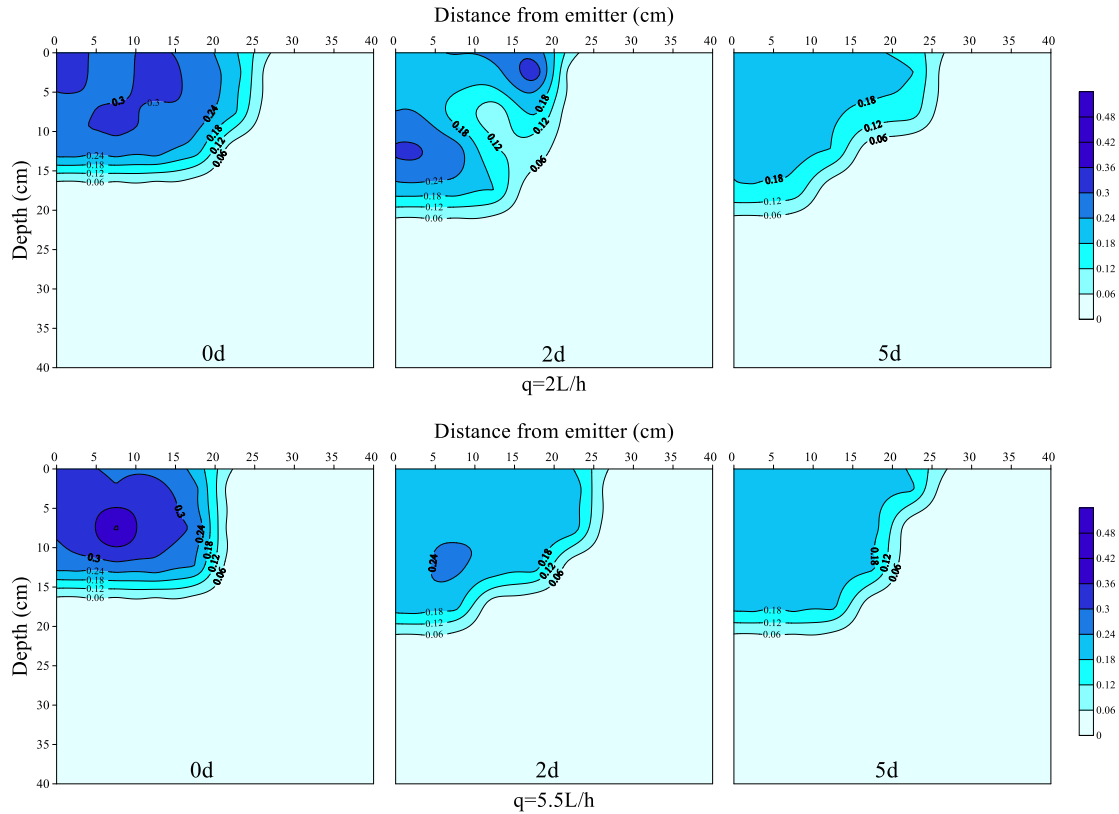


Figure 3-3 Isohydraulic contour map of soil moisture content at drip irrigation tape depth $H=0$ cm

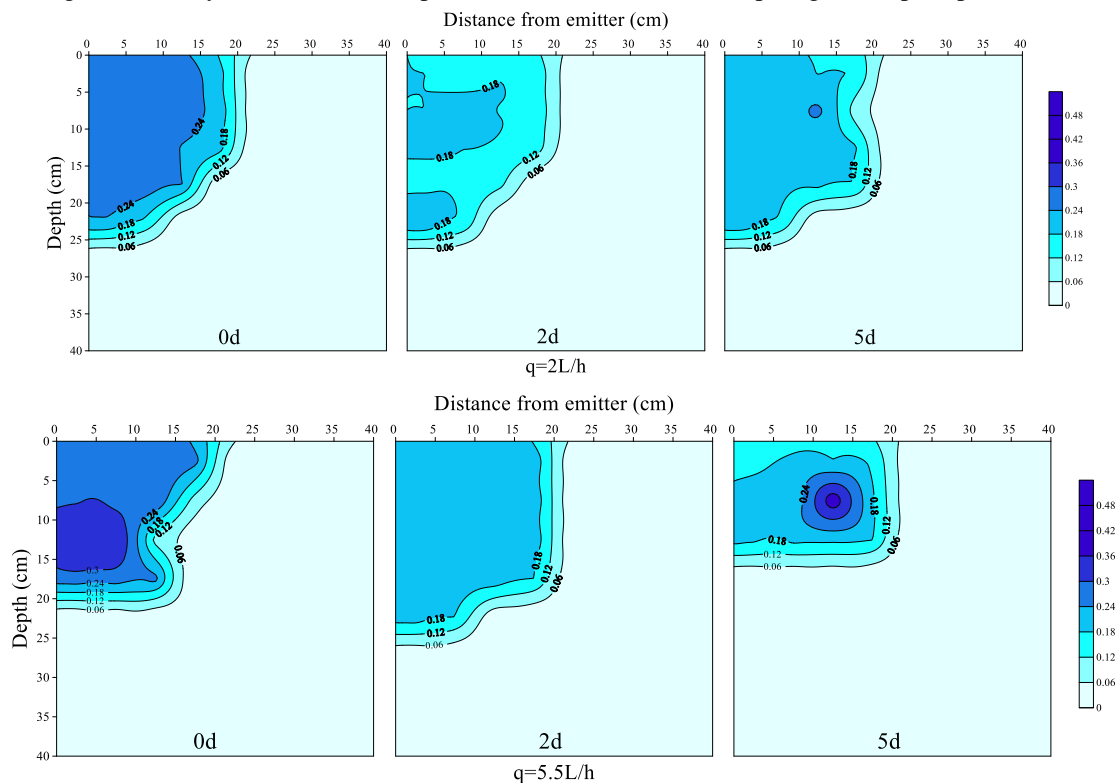


Figure 3-4 Isohydraulic contour map of soil moisture content at drip irrigation tape depth H=10 cm

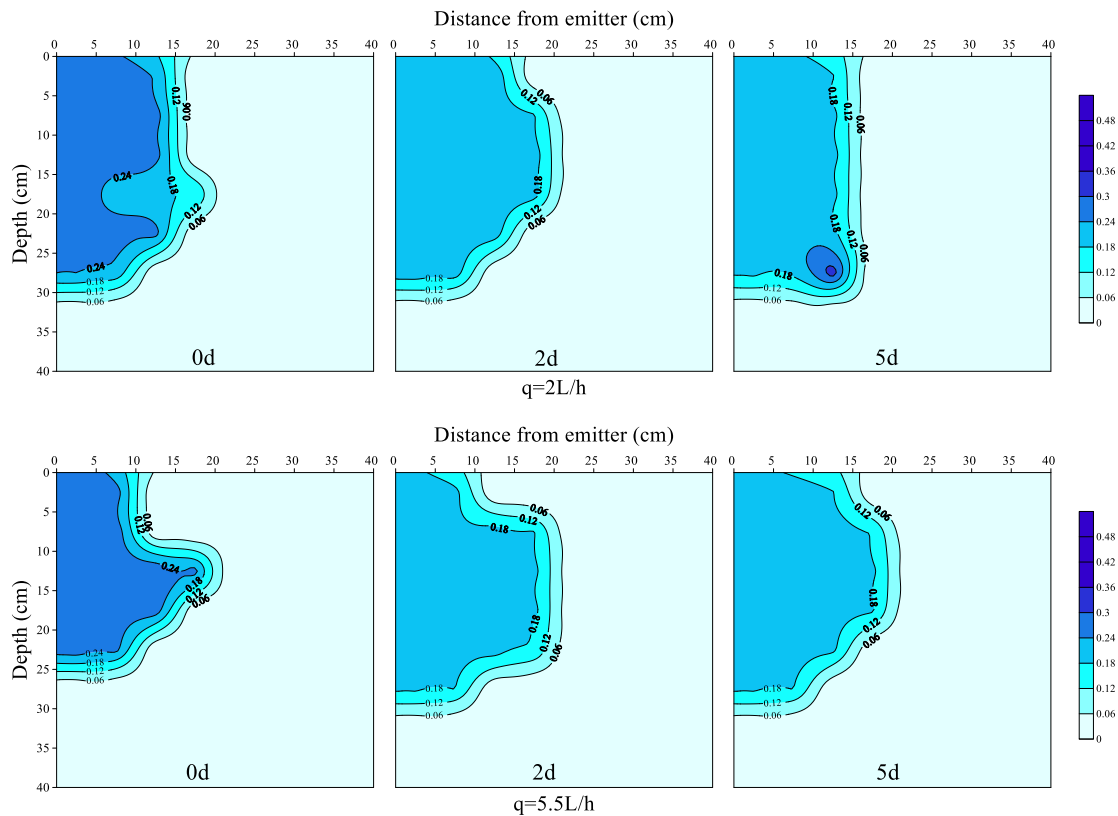


Figure 3-5 Isohydraulic contour map of soil moisture content at drip irrigation tape depth H=20 cm

3.2 Effects of Aeration Irrigation on Nitrogen Redistribution

3.2.1 Distribution Characteristics of Ammonium Nitrogen and Nitrate Nitrogen

Under conventional irrigation, ammonium nitrogen ($N-NH_4^+$) concentrates near the dripper, while nitrate nitrogen ($N-NO_3^-$) distributes at the wetting front edge, forming an "accumulation peak." Oxygenated irrigation significantly alters this pattern (Figure 3-6—3-11). Compared with conventional irrigation, under oxygenated irrigation treatment:

- (1) Reduction in ammonium nitrogen content: The concentration of ammonium nitrogen decreased more rapidly both near the emitters and throughout the wetted soil volume, particularly during the later stages of redistribution (5 days).
- (2) Increase in nitrate nitrogen content with more uniform distribution: The "accumulation peak" phenomenon of nitrate nitrogen was weakened, and its distribution range expanded. In the 30–40 cm deep soil layer, the nitrate nitrogen content under aerated irrigation was 5.35%–6.27% higher than that under conventional irrigation.
- (3) Decrease in soil pH: The soil pH under aerated irrigation was generally lower than that under conventional irrigation, showing a more pronounced acidification trend (Figure 3-12, 3-13 and 3-14), which is consistent with the stoichiometric relationship of H^+ production from nitrification.

These results indicate that oxygenated irrigation promotes the conversion of $N-NH_4^+$ to $N-NO_3^-$ (nitrification), accelerates the transformation and transport of nitrogen forms among utetheisa kong, but may also increase the risk of nitrogen leaching.

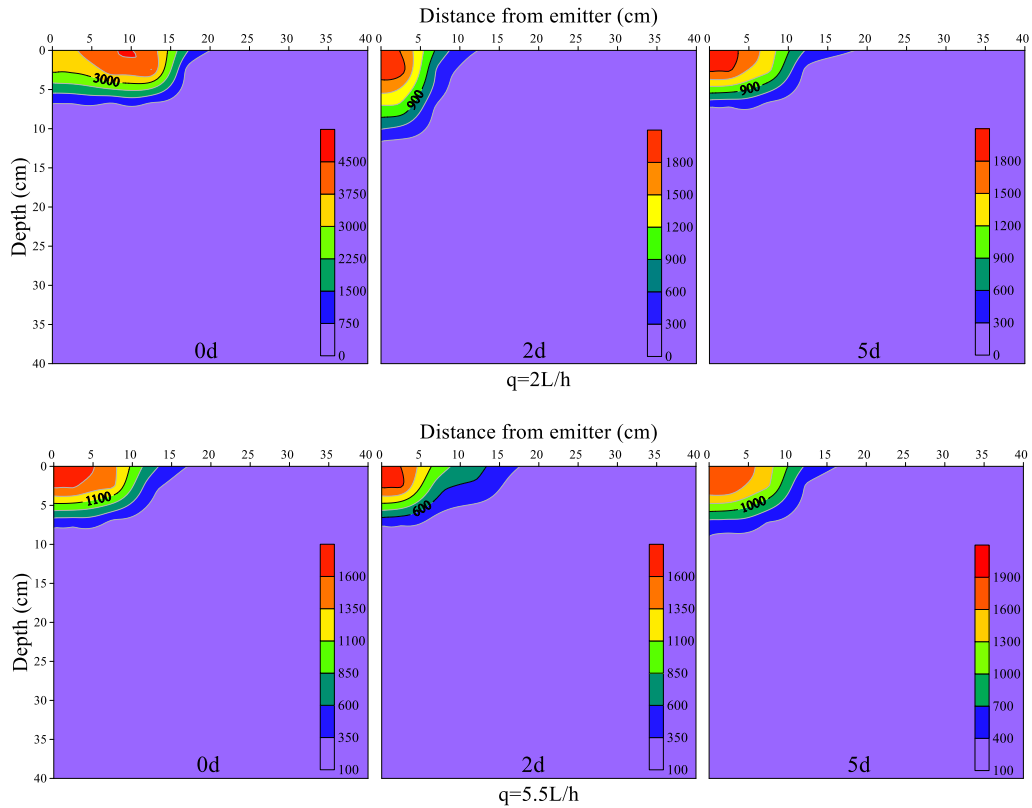


Figure 3-6 Isocline map of soil ammonium nitrogen at drip irrigation tape depth H=0cm

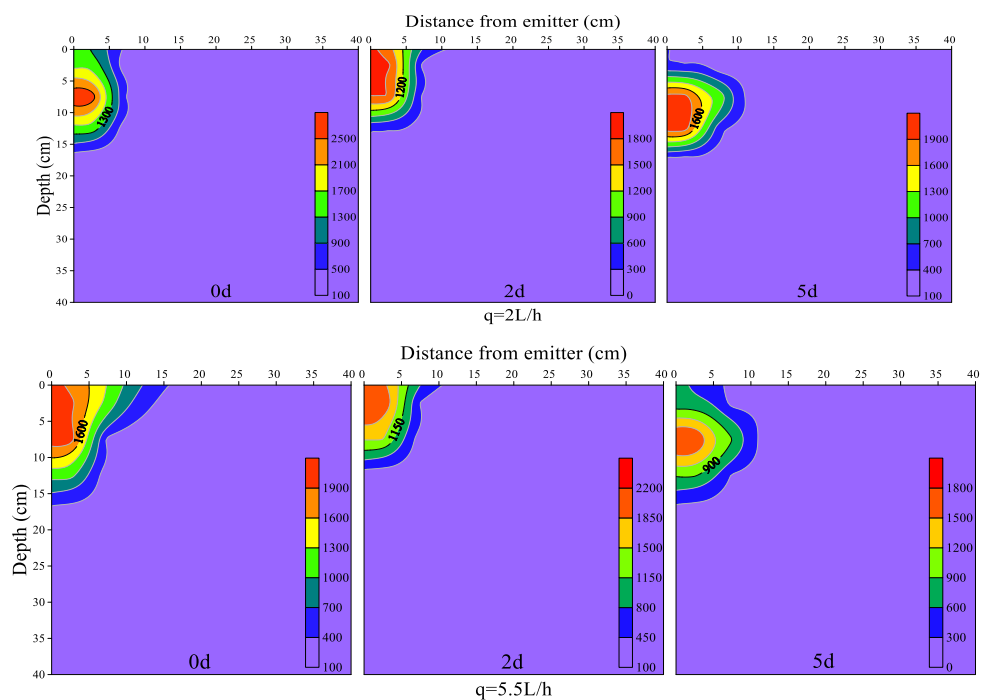


Figure 3-7 Isocline map of soil ammonium nitrogen at drip irrigation tape depth H=10cm

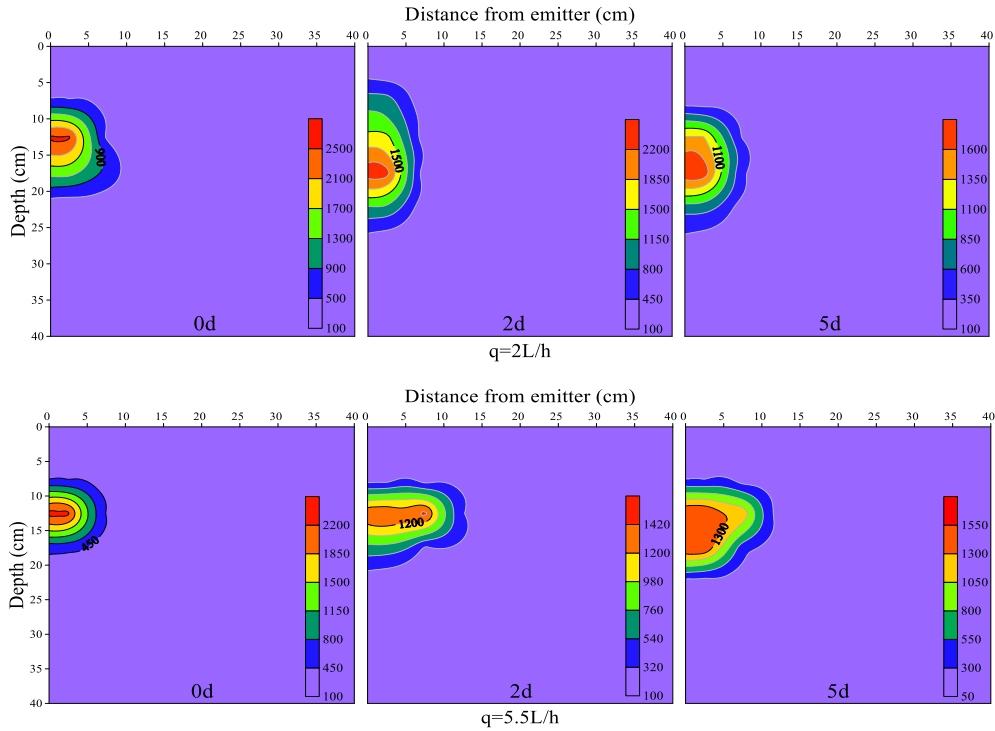


Figure 3-8 Isocline map of soil ammonium nitrogen at drip irrigation tape depth H=20cm

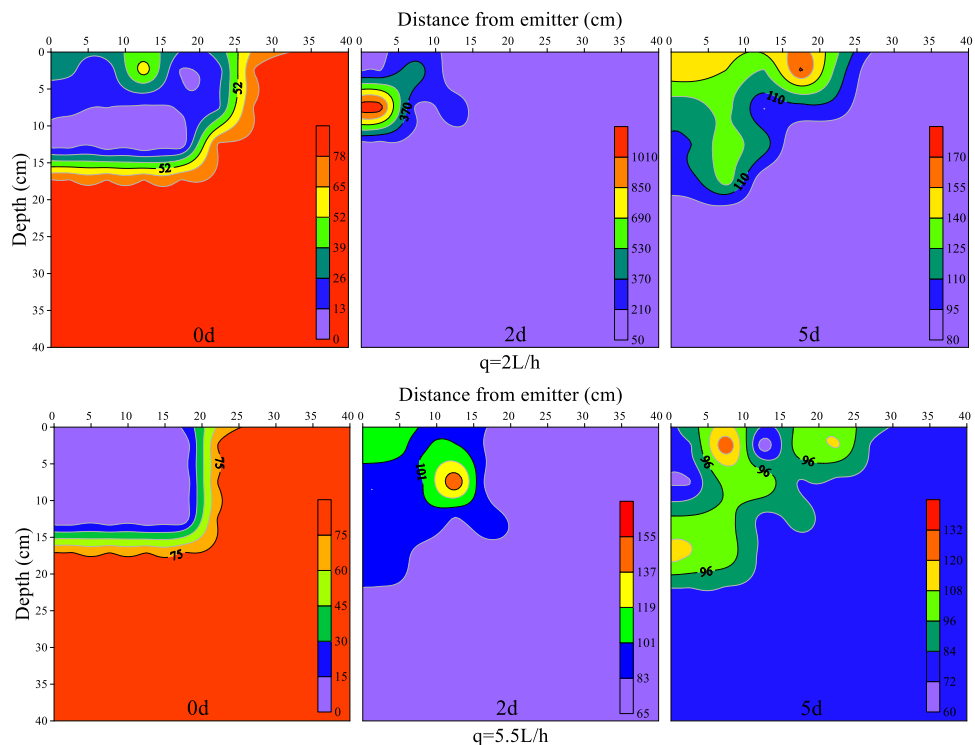


Figure 3-9 Isocline map of soil nitrate nitrogen at drip irrigation tape depth H=0cm

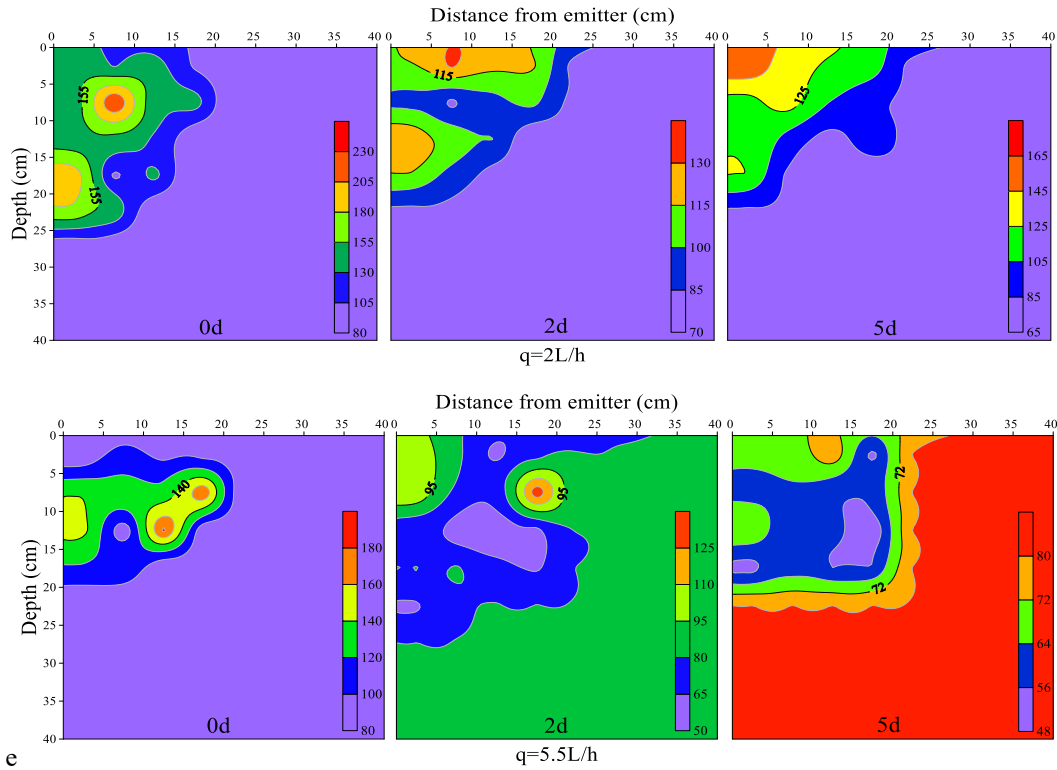


Figure 3-10 Isocline map of soil nitrate nitrogen at drip irrigation tape depth H=10cm

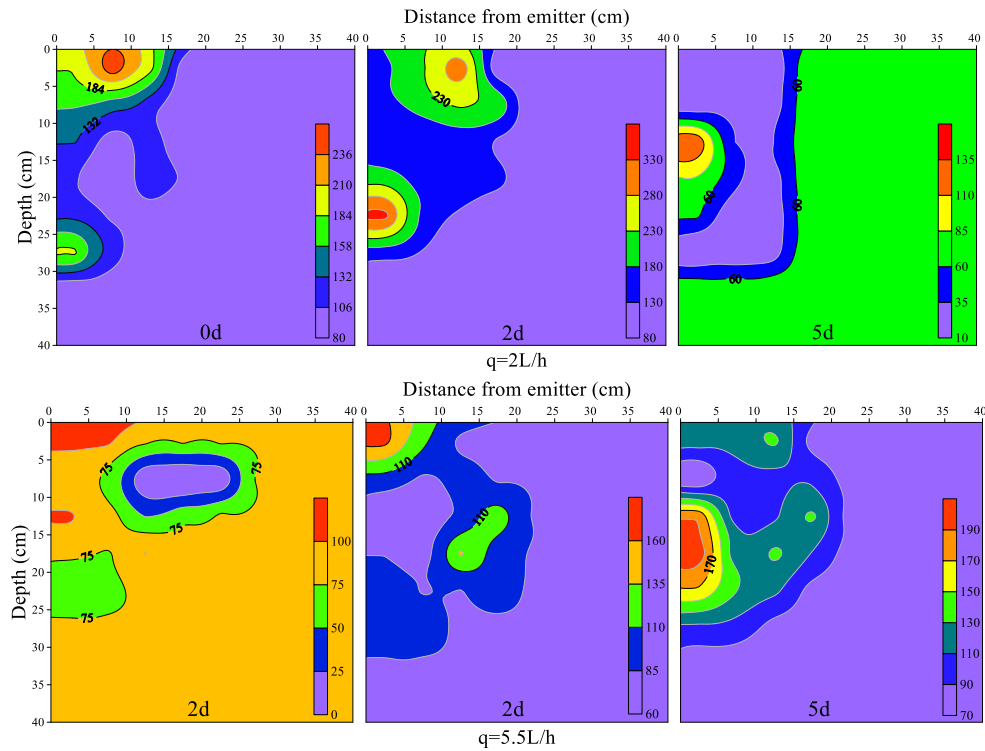


Figure 3-11 Isocline map of soil nitrate nitrogen at drip irrigation tape depth H=20cm

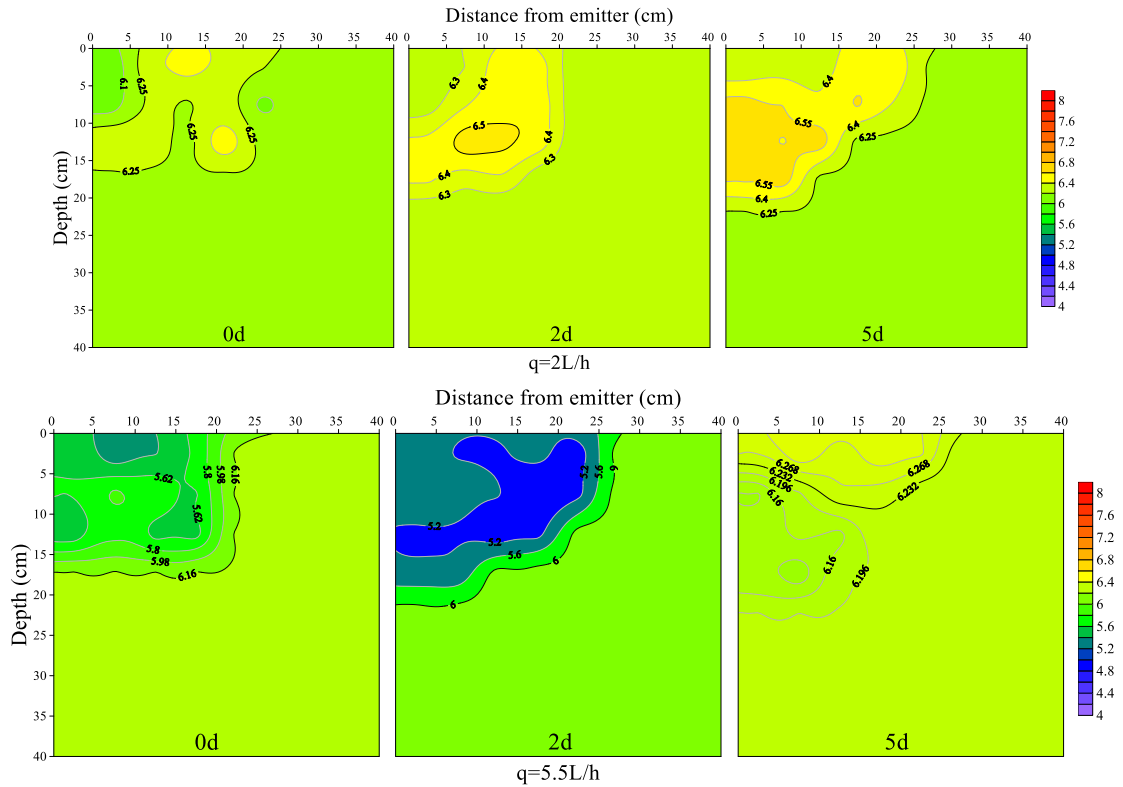


Figure 3-12 Soil pH isocline map at burial depth $H=0$ cm for drip irrigation tape

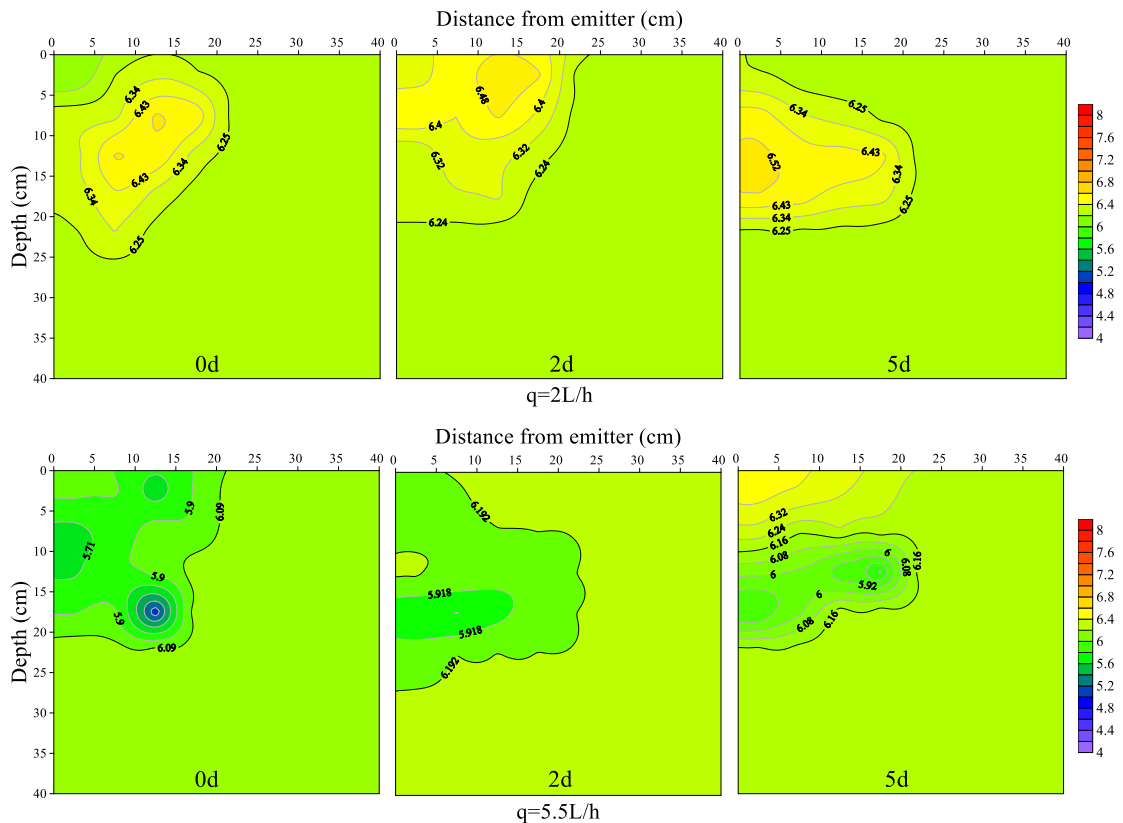


Figure 3-13 Soil pH isocline map at burial depth H=10 cm for drip irrigation tape

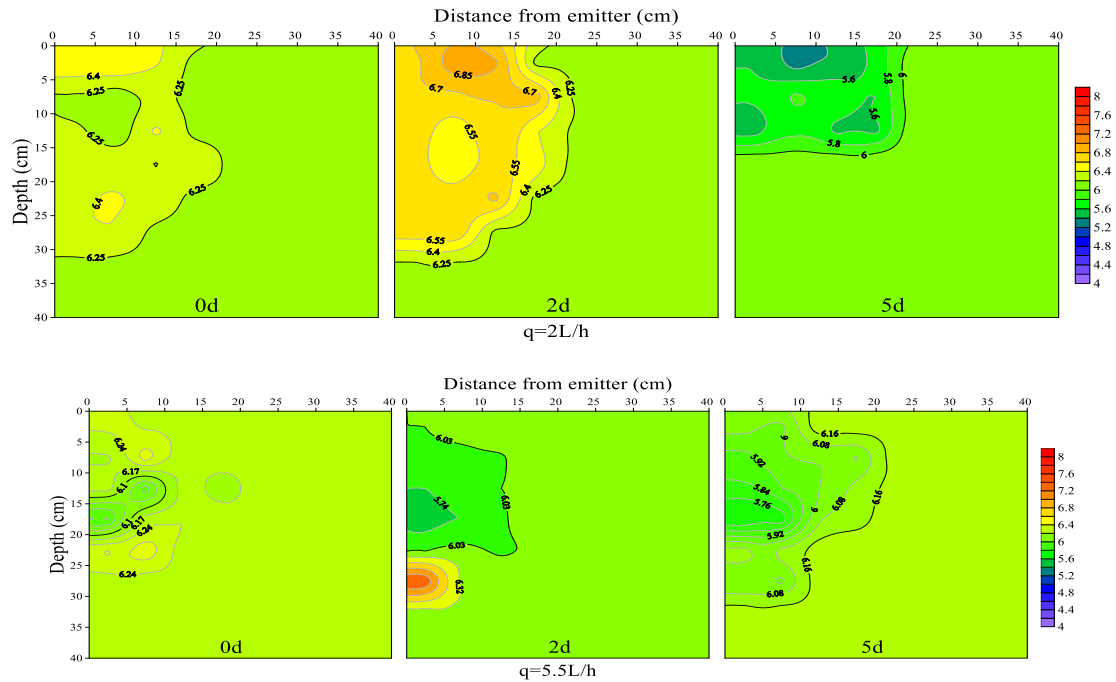


Figure 3-14 Soil pH isocline map at burial depth H=20 cm for drip irrigation tape

3.2.2 Microbial Mechanisms of Oxygenation-Promoted Nitrogen Transformation

To explain the aforementioned phenomenon, we analyzed the soil microbial metagenome of the key treatment (Figure 3-15).

- (1). Enhancement of nitrification functional genes: In the aerated irrigation treatment, the abundance of key functional genes *amoA* and *amoC* of ammonia-oxidizing archaea and bacteria was significantly higher than that in conventional irrigation ($p < 0.05$), while the abundance of genes associated with nitrite oxidation was also upregulated.
- (2). Enhancement of key microorganisms: The aerated treatment enriched aerobic nitrifying microorganisms such as *Nitrosospora* and *Nitrospira*.
- (3). Suppression of denitrification functional genes: Conversely, the abundance of some denitrification genes (e.g., *narG*) decreased in the aerated treatment, indicating that the anaerobic denitrification process was inhibited.

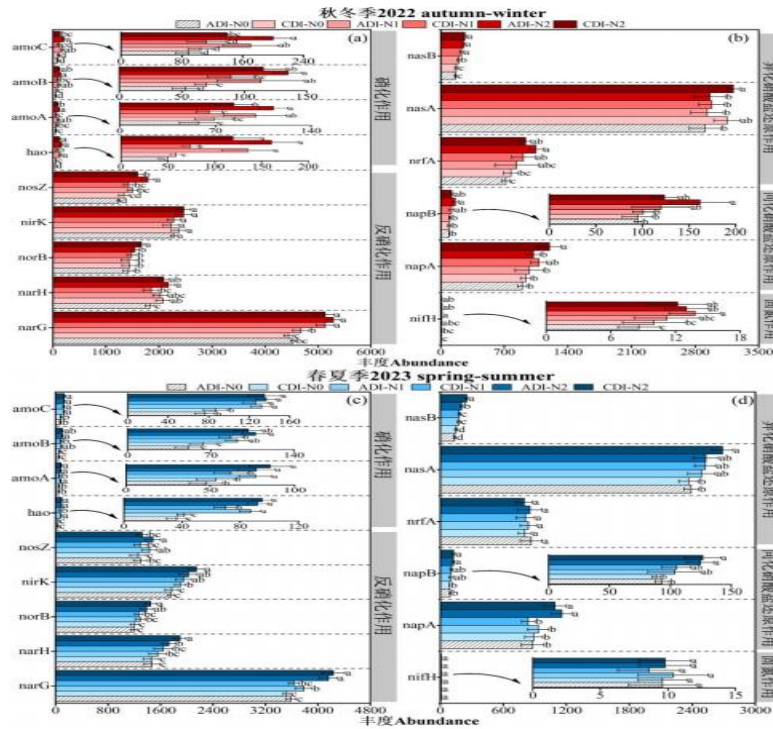


Figure 3-15 Effects of Irrigation Methods and Nitrogen Application on the Abundance of Functional Genes Involved in Soil Nitrogen Cycling

This microbial evidence directly demonstrates that oxygenated irrigation, by creating an oxygen-rich microenvironment, specifically enhances the activity of nitrifying bacterial communities, particularly *Parazacco spilurus* subsp. *spilurus*, thereby accelerating the biochemical conversion of ammonium nitrogen to nitrate nitrogen, which is also the fundamental cause of nitrate nitrogen accumulation and soil acidification.

IV. CONCLUSION

The study results demonstrate that: (1) Compared with conventional drip irrigation, aerated subsurface drip irrigation significantly alters the soil water redistribution pattern and promotes the vertical movement of the wetting front. A drip tape burial depth of 20 cm combined with aerated irrigation is most beneficial for replenishing deep soil moisture; a high emitter discharge rate (5.5 L/h) is more conducive to horizontal water expansion during the later stages of redistribution. (2) Aeration irrigation significantly accelerates the transformation process of soil nitrogen, manifested by a decrease in ammonium nitrogen content, an increase in nitrate nitrogen content, and a decline in soil pH. The accumulation of nitrate nitrogen in deep soil layers (30-40 cm) is 5.35%-6.27% higher than that under conventional irrigation, increasing the risk of leaching. (3) Oxygenated irrigation specifically enriched aerobic nitrifying microorganisms such as *Nitrosospora* by increasing soil dissolved oxygen and redox potential, particularly for *Parazacco spilurus* subsp. *spilurus*. It upregulated the expression of nitrification functional genes like *amoA* while simultaneously inhibiting the denitrification process, thereby explaining the mechanism of nitrogen form transformation from a microbial perspective.

V. ACKNOWLEDGEMENTS

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